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Elastic scattering of 1·17 and 1·33 MeV gamma rays by molybdenum, tantalum and lead*

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Abstract. Elastic scattering cross-sections of lead, tantalum and molybdenum were determined with the help of a Ge (Li) detector for 1·17 and 1·33 MeV rays between 30° and 115°. Theoretical evaluations of the cross-sections are based on a coherent addition of the well-known nuclear Thomson scattering amplitudes, the Rayleigh amplitudes calculated by Kissel and Pratt and the Delbrück amplitudes given by Papatzacos and Mork. The fairly good agreement between experiment and theory reveals the importance of the real Delbrück amplitudes. However, the experimental results in the 30–60° range tend to lie slightly but systematically below the calculated cross-sections.

Keywords. Gamma ray scattering; elastic scattering; lead; tantalum; molybdenum.

1. Introduction

Even after decades of effort, studies of elastic gamma ray scattering are being continued in order to elucidate several questions. In the case of scattering of gamma rays of energies around 1 MeV, the principal uncertainties are concerned with the amplitudes of Rayleigh scattering from the bound atomic electrons and Delbrück scattering from the nuclear Coulomb field. The other two coherent contributions, namely nuclear Thomson scattering and nuclear resonance scattering, are either well known or usually unimportant. During a period of about twelve years following the pioneering series of relativisitic calculations of *K*-shell Rayleigh scattering amplitudes (Brown and Mayers 1957), the Delbrück contribution was not emphasized in the interpretation of experiments (Dixon and Storey 1968), or found to be too small to be detected within experimental error (Standing and Jovanovich 1962) or treated as poorly known until the advent of more reliable calculations of Rayleigh amplitudes for outer shell electrons (Hardie *et al* 1970, 1971). Some of us (Basavaraju and Kane 1970) pointed out that the 1·12 and 1·33 MeV results, obtained at large angles with a sodium iodide detector, could not be understood on the basis of the then available Rayleigh amplitudes, unless an account was taken of the real part of the Delbrück amplitude for scattering with polarisation change or the spin-flip Delbrück amplitude. In an empirical attempt to understand the results for the

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scattering of 1·33 MeV gamma rays by lead through an angle of about 125°, a value (−0·0060) r_0 was suggested for the real spin-flip Delbrück amplitude. The negative sign indicates a destructive interference with the corresponding Rayleigh amplitude. Here, r_0 is the classical electron radius and is equal to e^2/mc^2, e and m are the charge and the mass of an electron, and c is the velocity of light. A similar result was obtained by other workers (Schumacher *et al* 1973 and Smend *et al* 1973). The only available theoretical calculation (Ehlotzky and Sheppey 1964) gave a value of about +0·0016 r_0. Thus, a major discrepancy was present.

Improved and extended calculations (Papatzacos and Mork 1975) of the Delbrück amplitudes did not remove the discrepancy. In the meantime, Schumacher *et al* (1975 and 1976) reported new measurements with 2·75 MeV gamma rays and presented strong evidence for the real Delbrück amplitudes at this energy. On the basis of a fresh analysis of the available results, they suggested the possibility of numerical errors in the Rayleigh amplitudes for 1·33 MeV calculated by Brown and Mayers (1957). This suggestion has been confirmed recently (Kissel and Pratt 1978).

In view of the above mentioned situation, we felt that new Ge(Li) detector measurements would be worthwhile particularly if performed over an extensive angular range and with targets of different atomic number Z. The present paper describes these measurements and an analysis of data on the basis of the improved calculations. There is now good agreement between experiment and theory. Thus, the role of the real Delbrück amplitudes for 1·33 MeV has been clearly shown.

A report has been given recently (Kane *et al* 1978) concerning the elastic scattering of 1·17 and 1·33 MeV gamma rays by lead through angles between 4·5° and 8°. An interpretation of these small angle scattering measurements requires a precise knowledge of no-spin-flip Rayleigh amplitudes for all atomic shells. An accurate relativistic calculation along the lines of Brown and Mayers becomes prohibitively laborious in the case of outer shell electrons on account of the large number of higher multipole terms that have to be considered. In such cases, a modified form factor approximation has been found to be appropriate (Brown and Mayers 1957; Kissel and Pratt 1978). The desirability of extensive relativistic calculations of modified form factors was suggested in our above mentioned paper.

The details of the present experiments are described in § 2. The corrections and errors are outlined in § 3. Methods of obtaining theoretical values of elastic scattering cross-sections are given in § 4. Results and conclusions are presented in § 5.

2. Experimental details

2.1. *Geometrical arrangement and electronics*

The experimental arrangement for a scattering angle of 50° is shown in figure 1. S was a cobalt-60 source of approximately 300 mCi strength and had the shape of a cylinder with 1 cm height and 1 cm diameter. The source was kept at the centre of a cylindrical lead housing of 35 cm diameter and 35 cm height. The source-to-target distance was usually 49 cm. The target-to-detector distance varied between 22·4 cm at 115° and 56·0 cm at ∼ 30°. The lead target was circular with a diameter of 15·1 cm. The tantalum and molybdenum targets were rectangular with dimensions 8·4 × 8·4 cm and 10·8 × 11·5 cm respectively. The target face made an angle ϕ with a vertical plane

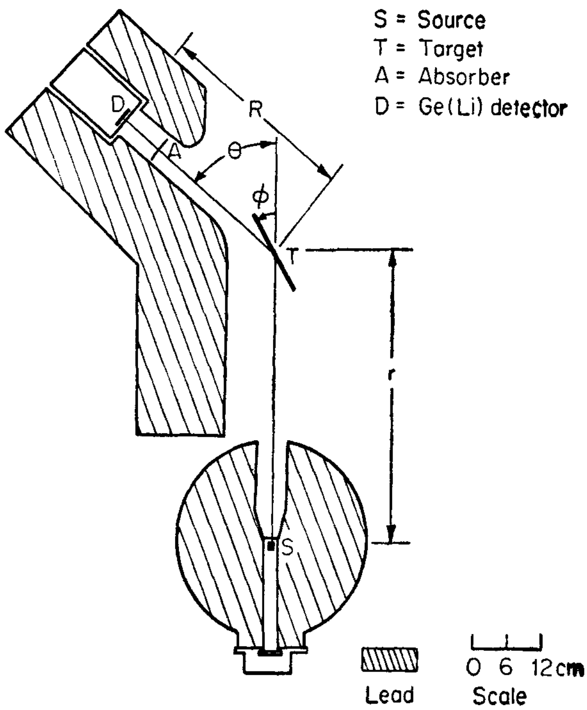

Figure 1. Experimental arrangement during measurements at 50°. S is the Cobalt-60 source. *T* is the target under study. *A* is a lead absorber in front of the Ge (Li) detector *D*.

passing through the target centre and containing the incident photon beam direction. In the reflection geometry, the spread of scattering angles was minimised by choosing the angle ϕ such that equation (1) was satisfied.

$$\sin\phi/\sin(\theta-\phi)=r/R, \tag{1}$$

where θ is the scattering angle. The thickness of a target along the incident beam direction was equal to the product of the normal target thickness and cosec ϕ, and was about 0·8 times the mean free path. Uncertainties in the efficiency—solid angle product of the detector were eliminated in the usual way by the use of an auxiliary weak source w, of strength either 8 or 180 micro-Ci, at the scatterer position. Then, the elastic scattering cross-section $d\sigma/d\Omega$ is determined with the help of equation (2).

$$d\sigma/d\Omega = (w/s)\,(N_s/N_w)\,(1/n)\,(r^2/T)_{\text{av}}. \tag{2}$$

Here s is the strength of the main source, N_s is the rate of detection of elastically scattered photons, N_w is the rate of detection with the weak source alone, n is the number of scattering atoms and is equal to N_0M/A, N_0 is Avogadro's number, M is the mass of the scatterer, A is the atomic weight of the scatterer, T is a transmission factor and the subscript $(\ )_{\text{av}}$ indicates an average over the target. $(r^2/T)_{\text{av}}$ was computed by dividing the target into more than one thousand elements. The weak source was also used for the determination of the pulse height distribution of the direct gamma rays, designated as the calibration spectrum.

A planar Ge(Li) detector of about 3·8 cm diameter and an active volume of 10 cc was used during the measurements. The electronics was of the standard type including an FET preamplifier, an active filter amplifier, a biased amplifier and a 512-channel pulse height analyser built by the Electronics Corporation of India Limited. The full width at half maximum (fwhm) of the photopeak was approximately 5 keV for 1·33 MeV gamma rays.

2.2. *Measurements*

A major fraction of the scattered beam consists of low energy photons produced in the target as a consequence of photo-electric and Compton processes, and by secondary processes such as bremsstrahlung. Therefore, the total rate could be reduced substantially by the use of a lead absorber of 3 to 7 g/cm^2 thickness (A in figure 1). The total count rates were typically about 10^3 per second. In order to minimise small errors arising from possible count rate dependent effects, the background was determined with a low Z dummy target of perspex. The thickness of the perspex was chosen in such a way that the total rate was approximately the same as that with the target under study. Since the elastic scattering cross section of low Z elements is negligibly small at energies of about 1 MeV, the contribution of the perspex target in the neighbourhood of the 1·33 MeV photopeak is negligible. Of course, other effects such as electronic noise and radioactive contaminations in materials make the same contribution to the photopeak during background runs as that during

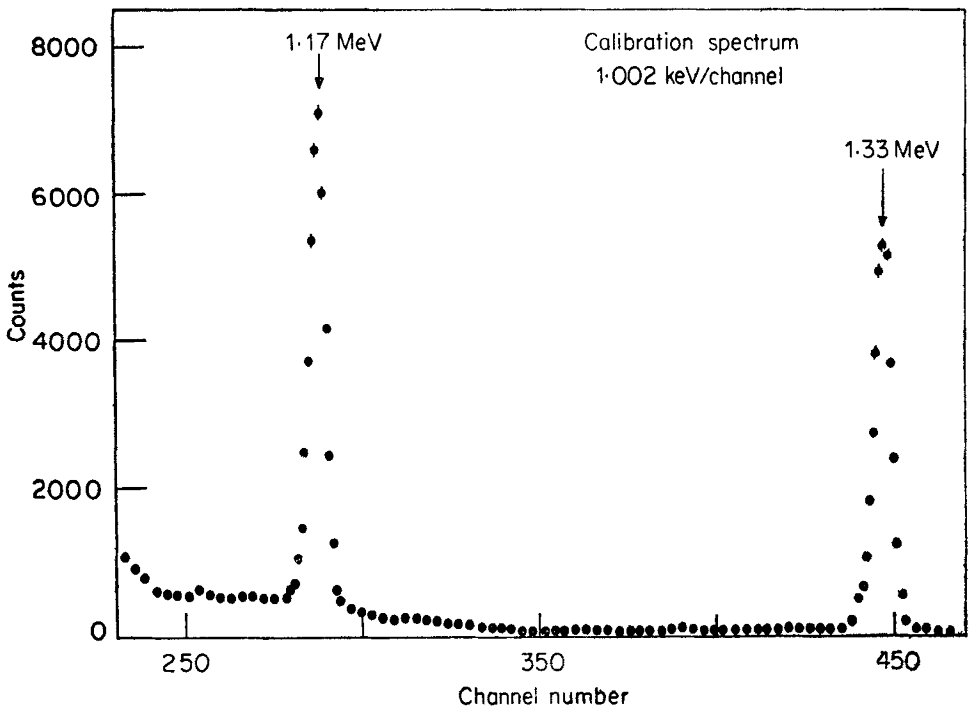

Figure 2. Pulse height distribution of the direct gamma rays from a weak source. A biased amplifier was used to expand the region of interest. Except in the photopeak regions, every third point is shown in the interest of clarity.

the scattering runs. In the case of the 1·33 MeV photopeak, the background counts were approximately one fifth of the counts determined with a lead target during back angle measurements.

A typical calibration spectrum is shown in figure 2. Two scattered beam pulse height distributions, displayed in figures 3 and 4, represent the net counts in each channel obtained by a subtraction of the background counts from the corresponding counts measured with the given target. In the case of 1·33 MeV gamma rays, the photopeak area in figure 2 was used to determine N_w and the photopeak areas of scattered beam pulse height distributions were used to determined N_s. In the case of 1·17 MeV gamma rays, a correction described in § 2.3 has to be considered before the values of corresponding count rates are determined.

The ratio w/s of the strength of the calibration source to that of the main source was determined according to well-known methods (Standing and Jovanovich 1962; Varier 1978). On the basis of the measurements for 1·17 and 1·33 MeV gamma rays, the ratio in the case of the weaker calibration source was found to be $(2{\cdot}67 \pm 0{\cdot}08) \times 10^{-5}$ and $(2{\cdot}61 \pm 0{\cdot}08) \times 10^{-5}$ respectively. The two values are consistent with each other.

2.3. *Continuum between the photopeaks*

The photopeak of 1·17 MeV rays lies between the photopeak of 1·33 MeV gamma

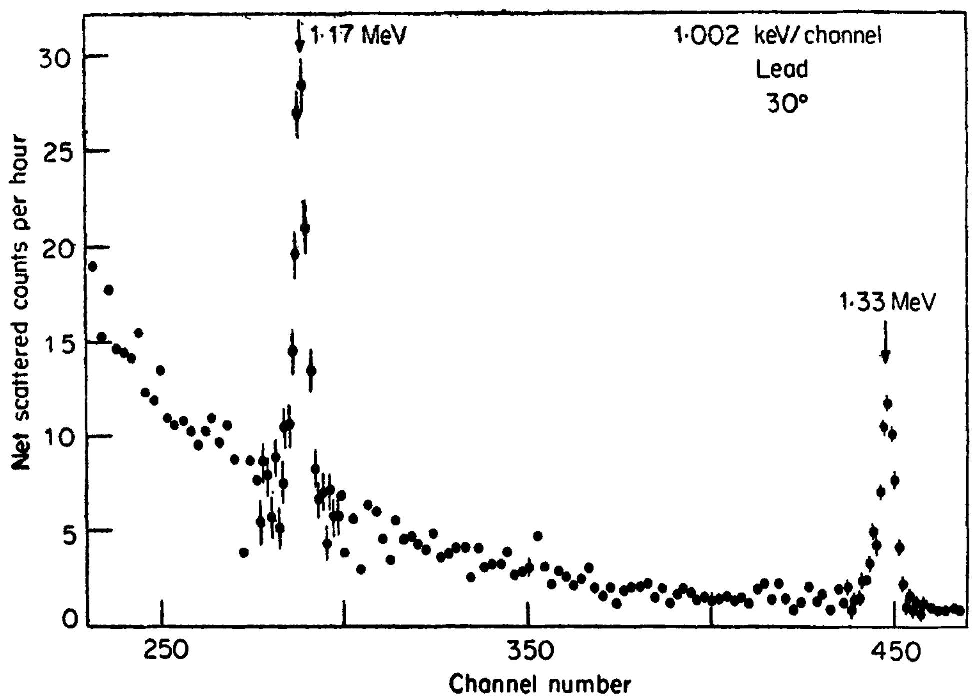

Figure 3. Pulse height distribution of gamma rays after scattering through 30·3° by a lead target. The data are based on measurements with the lead target for 17 hr and background measurements for 12 hr. The lead absorber in front of the detector had a thickness of 3·4 g/cm². In figures 3 and 4, except in the photopeak regions, only alternate points are shown and the error bars are drawn on only a few points.

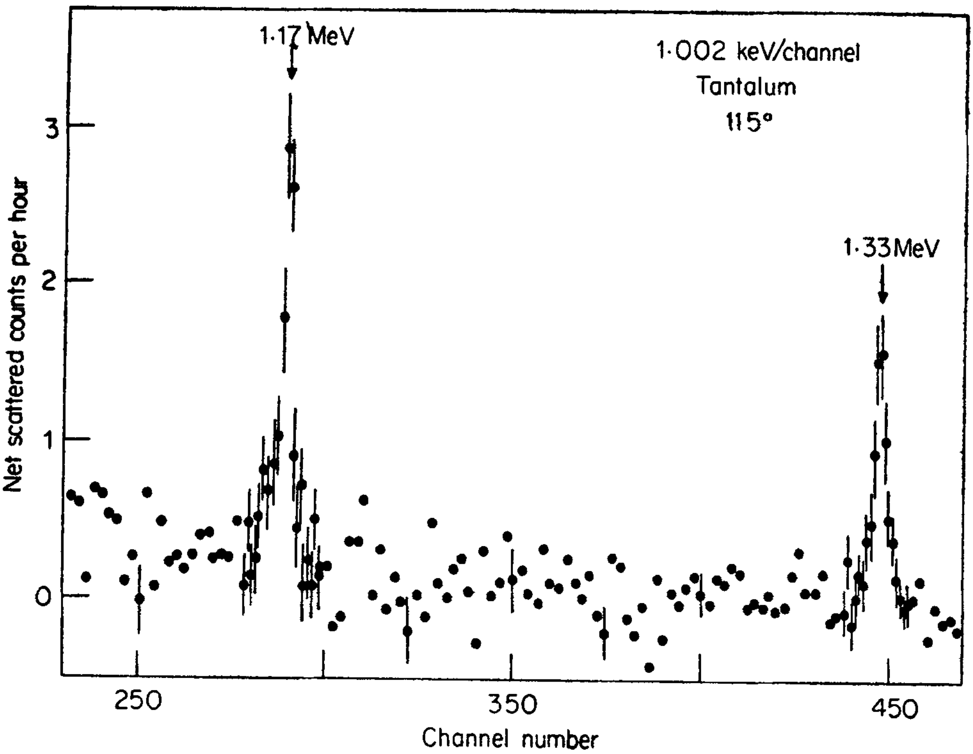

Figure 4. Pulse height distribution of gamma rays after scattering through 115° by a tantalum target. The data are based on measurements with the tantalum target for 56 hr and background measurements for 33 hr. The lead absorber thickness was 3·4 g/cm². Note that the $y=0$ point is shifted up in order to show small negative values of net counts in some of the channels.

rays and their Compton edge at about 1·12 MeV. However, figures 2 to 4 clearly show an appreciable continuous pulse height distribution between channels corresponding to 1·17 and 1·33 MeV.

Firstly, we will consider the calibration spectrum. The Compton scattering of 1·33 MeV gamma rays through small angles by air or by materials close to the source and the detector, and inefficient charge collection in the detector can give rise to the continuum in channels below the 1·33 MeV photopeak. Thus, although the observed counts in the 1·17 MeV photopeak channels arise mainly from 1·17 MeV gamma rays, effects of the type mentioned above contribute a small but measurable fraction of these counts. In a separate experiment with several monoergic gamma sources, the continuum could be approximated by straight lines according to the least squares fitting procedure. The results of this experiment were used to determine the channel-wise counts in the continuum expected with a given intensity of the 1·33 MeV photopeak. The area a_w under the continuum and confined to twenty channels around the 1·17 MeV photopeak was determined. By subtracting a_w from the area under the calibration spectrum and confined to the same twenty channels, we obtained the photopeak counts N_w arising from 1·17 MeV gamma rays alone.

Several additional effects can also contribute to the similar continuum in the case of the scattered beam pulse height distribution. These are Compton scattering from strongly bound electrons in the scatterer, pile up generated pulse height modifications, multiple scattering in the scatterer and bremsstrahlung from electrons released in the target through photoeffect or Compton processes. We find that only the first effect is significant in our data such as those displayed in figures 3 and 4.

As mentioned in § 2.2, the total count rates were about 10^3 per second. Counts in twenty channels around the 1·33 MeV photopeak were unchanged within the experimental error when measurements were made with or without the dummy perspex target. Thus, the pile up effect was negligible.

The contribution of multiple scattering and bremsstrahlung was studied at 30° by measurements with three different lead targets of normal thicknesses t between 1·1 g/cm² and 3·29 g/cm². The angle 30° was chosen in order to determine the maximum possible contribution of multiple scattering and bremsstrahlung effects in our experiment. The quantity N_c/Tt was found to be independent of t within the experimental error of about 3%. Here, N_c is the count rate in the channels between 1·2 and 1·3 MeV. During the actual cross-section measurements at 30·3°, the normal lead target thickness was 1·1 g/cm². Thus, the secondary processes are not important in our measurements. An approximate theoretical estimate provided additional confirmation of this conclusion.

When a photon suffers Compton scattering from a bound electron, the total momentum in the final state is shared by the scattered photon, the ejected electron and the recoil ion. Consequently, the scattered photon energy extends from zero almost upto a value which is equal to the difference between the initial photon energy and the binding energy of the electron. For example, in the case of such scattering of 1·33 MeV gamma rays from lead K shell electrons, the scattered photon energy can extend up to 1·24 MeV. The experimental results are summarised in table 1 in which a_s represents the empirically determined area of the continuum underlying the 1·17 MeV photopeak in the scattered beam pulse height distribution. A detailed discussion of theories applicable to scattering from K shell electrons has been given recently (Kane and Baba Prasad 1977).

For the present limited purpose of estimating a correction for the presence of the related continuum, a simpler formulation was used (Schumacher 1971). It is seen from table 1 that the estimated K shell electron contribution is about 40-70% of the empirical correction a_s. Thus, a fair understanding of the pulse height continuum between the two photopeaks is available.

Table 1. Net scattered beam counts N'_s per hour with a lead target in the neighbourhood of 1·17 MeV channels and estimated corrections. a_s is obtained empirically from a straight line fit to the continuum below the 1·33 MeV photopeak (for details refer to § 2.3). In the last column, a theoretical estimate is given for the correction arising from Compton scattering of 1·33 MeV gamma rays by only the K shell electrons of lead. The intensity N_s of elastically scattered 1·17 MeV gamma rays is equal to $N'_s - a_s$ and is not separately given. Distances between the scatterer and the detector, and counting periods were different at different scattering angles θ.

θ (degrees)	N'_s	Empirical correction a_s	K shell Compton correction
30·3	169 ± 6	53 ± 13	39
50	131 ± 3	54 ± 3	33
70	61·2 ± 1·6	24·8 ± 2·2	12
90	72·6 ± 1·4	23·6 ± 3·7	9
115	47·0 ± 1·4	11·6 ± 1·6	5

The intensity N_s of 1·17 MeV elastically scattered gamma rays was determined by subtracting a_s from the observed total number N'_s of counts in the twenty channels around 1·17 MeV. The ratio $(N_s/N_w)\times 10^3$ varied between $3{\cdot}36\pm0{\cdot}18$ to $87{\cdot}6\pm9{\cdot}5$ for the lead target, between $1{\cdot}07\pm0{\cdot}12$ to $27{\cdot}8\pm3{\cdot}8$ for the tantalum target and between $0{\cdot}34\pm0{\cdot}08$ to $5{\cdot}3\pm3{\cdot}1$ for the molybdenum target, the larger values corresponding in each case to 30·3° measurements. In the case of 1·33 MeV gamma rays, the ratios were somewhat smaller and reflected the decrease of elastic scattering cross section with increasing energy.

3. Corrections and errors

It should be noted that the total count rates during calibration, background and scattering runs were approximately the same. However, the pulse height distributions are not exactly the same in the three cases. Therefore, a correction for dead time effects was experimentally determined according to a method suggested by Strauss *et al* (1968). Pulses from a constant frequency precision pulse generator were fed to the input of the pre-amplifier along with the pulses from the detector. First, the pulser spectrum was recorded without any gamma ray beam on the detector. Then, the gamma rays either from the calibration source or the dummy perspex target or the target under study were allowed to fall on the detector and the pulser spectrum was again recorded in each case. From the difference between the pulser counts with and without a gamma ray beam, the loss of counts due to dead time effects was determined. This loss, expressed as a fraction of the pulser frequency, gives the fractional correction to be applied to the data. The correction varied with scattering angle but was always less than 4%.

Cross-sections were corrected for finite angular spreads according to the method described recently (Kane *et al* 1978). The slightly asymmetrical spreads of angles around mean values were also taken into account. The downward correction for a lead target was only 3% at 30·3° on account of the large target to detector distance, 6% at 50° and less than 1% at the three larger angles. Similar but smaller corrections were applied for tantalum and molybdenum cross-sections. The impurity content of the target materials was found to be less than 0·3% and was considered small.

The statistical error in N_w was less than 1%. Similar errors in N_s varied between 3 to 5% for the lead target, between 5-10% for the tantalum target and between 20-50% for the molybdenum target. In the case of 1·17 MeV measurements, the statistical errors were usually smaller but additional errors on account of the continuum, described in § 2.3, had to be considered. The error in the value of $(r^2/T)_{\text{av}}$ was estimated to be less than 2%. The final error was obtained by combining the different errors in quadrature.

4. Theoretical estimates of cross sections

The nuclear Thomson scattering amplitudes for no-spin-flip and spin-flip situations are respectively

$$-\frac{Z^2m}{2M_n}(1+\cos\theta)\,r_0 \text{ and } \frac{Z^2m}{2M_n}(1-\cos\theta)\,r_0,$$

where M_n is the mass of the nucleus. The nuclear resonance scattering contribution to the total elastic scattering amplitude comes mainly from the low energy tail of the giant resonances. On the basis of a knowledge of the photonuclear parameters (Vyssiere *et al* 1970), this contribution can be shown to be less than 1% of the dominant Rayleigh amplitude and is neglected.

The Rayleigh amplitudes were determined as follows. Accurate relativisitc amplitudes are now available (Kissel and Pratt 1978) in the case of lead, tungsten and samarium for 1·33 MeV, and in the case of lead for 1·17 MeV. The Rayleigh amplitudes in the case of tantalum for 1·33 MeV were obtained by a smooth interpolation between the three calculated values. In the case of tantalum for 1·17 MeV, and molybdenum for 1·17 and 1·33 MeV, the Rayleigh amplitudes were calculated with the help of the formulae given by Smend and Schumacher (1974a and b). The starting points in the present calculations were the numerical lead K shell amplitudes given by Kissel and Pratt.

The required no-spin-flip and spin-flip K shell amplitudes $a_{\mathrm{RK}}^{\mathrm{NSF}}$ and $a_{\mathrm{RK}}^{\mathrm{SF}}$ in the case of tantalum for 1·17 MeV are then given by equations (3) and (4).

$$a_{\mathrm{RK}}^{\mathrm{NSF}}(1{\cdot}17, \mathrm{Ta}) = a_{\mathrm{RK}}^{\mathrm{NSF}}(1{\cdot}17, \mathrm{Pb})\,\frac{g_K(1{\cdot}17, \mathrm{Ta})}{g_K(1{\cdot}17, \mathrm{Pb})}. \tag{3}$$

$$a_{\mathrm{RK}}^{\mathrm{SF}}(1{\cdot}17, \mathrm{Ta}) = a_{\mathrm{RK}}^{\mathrm{SF}}(1{\cdot}17, \mathrm{Pb})\,\frac{f_K(1{\cdot}17, \mathrm{Ta})}{f_K(1{\cdot}17, \mathrm{Pb})}. \tag{4}$$

Here, f_K and g_K are the form factors and the modified form factors respectively for the energy and the target mentioned in the brackets. The L shell amplitudes in the case of tantalum for 1·17 MeV were obtained by a similar procedure except that f_K (1·17, Ta) and g_K (1·17, Ta) were replaced by the corresponding quantities f_L (1·17, Ta) and g_L (1·17, Ta). The spin-flip amplitudes for M, N and higher shells were calculated in the form factor approximation. The M, N and higher shell no-spin-flip amplitudes, being small in the angular range under consideration, were neglected. An analogus procedure was followed in the case of molybdenum.

According to Papatzacos and Mork (1975), the imaginary parts of the Delbrück amplitudes are negligible in comparison with the real parts for 1·33 MeV and consequently also for 1·17 MeV. This conclusion has not been substantially altered by the recent evaluation of Bar-Noy and Kahane (1977), which gives somewhat larger values for the imaginary Delbrück amplitudes. The real Delbrück amplitudes are only of the order of 10% of the Rayleigh amplitudes for energies under consideration. Thus, the imaginary Delbrück amplitudes could be neglected. It should be noted that the calculated real Delbrück amplitudes do not include as yet the contribution of Coulomb corrections.

The nuclear Thomson amplitudes were combined coherently with the real parts of the Rayleigh and the Delbrück amplitudes to give A^{NSF} and A^{SF}. The imaginary parts of the Rayleigh amplitudes, A_i^{NSF} and A_i^{SF}, were evaluated separately. The elastic scattering cross section was then calculated with the help of equation (5).

$$d\sigma/d\Omega = (A^{\mathrm{NSF}})^2 + (A^{\mathrm{SF}})^2 + (A_i^{\mathrm{NSF}})^2 + (A_i^{\mathrm{SF}})^2. \tag{5}$$

Table 2. Elastic scattering cross-sections (10^{-30} cm^2/sr) for 1·17 MeV and 1·33 MeV gamma rays*

Angle (degrees)	1·17 MeV			1·33 MeV		
	Lead	Tantalum	Molybdenum	Lead	Tantalum	Molybdenum
30·3	13000 ± 1500	10400 ± 1500	520 ± 320	7720 ± 430	3370 ± 410	300 ± 160
50	937 ± 56	451 ± 80	11 ± 11	481 ± 22	240 ± 28	26 ± 5
70	248 ± 26	82 ± 15	3 ± 3	146 ± 11	68 ± 10	3 ± 2
90	169 ± 15	67 ± 15	4·3 ± 2·0	106 ± 6	57 ± 5	4·5 ± 0·8
115	146 ± 9	69 ± 8	6·8 ± 1·6	101 ± 6	48 ± 4	4·3 ± 0·9

*The earlier results (Basavaraju and Kane 1970) for lead and tantalum, obtained with a sodium iodide detector and 1·33 MeV gamma rays, are 120±11 and 58·1±9·4 respectively at 90°, and 93·8±9·1 and 56·6±6·7 respectively at 124·5°.

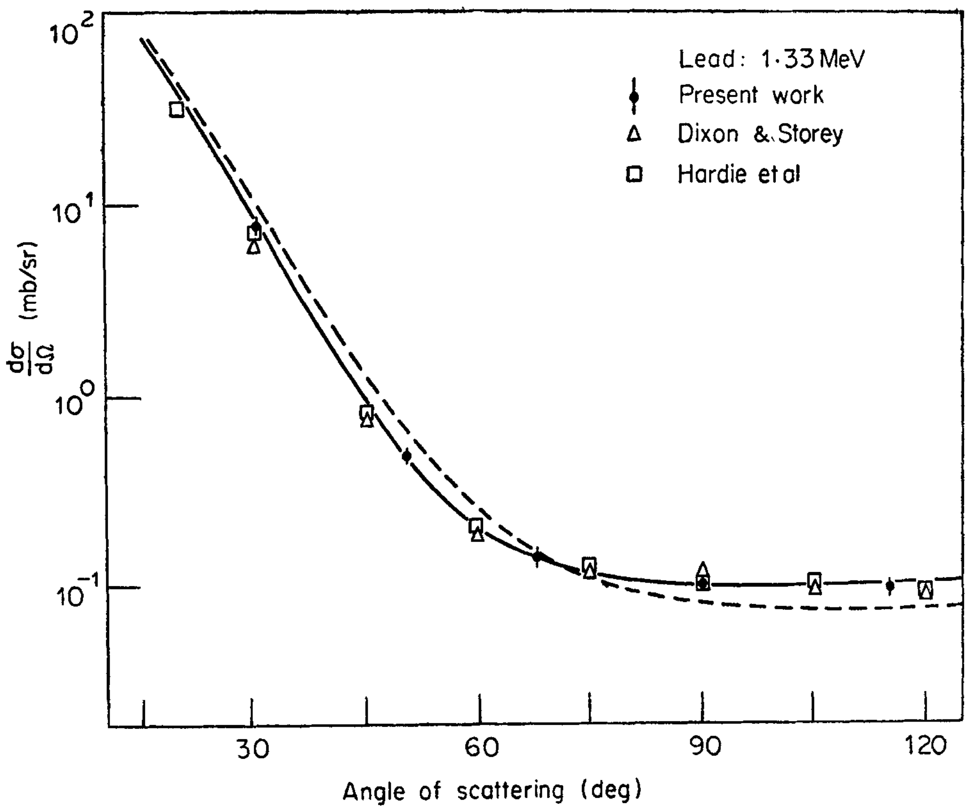

Figure 5. Elastic scattering cross sections of lead for 1·33 MeV gamma rays. The dashed curves in figures 5 to 8 represent theoretical cross-sections obtained by neglecting the Delbrück contribution. The solid curves in figures 5 to 8 include the Delbrück contribution.

5. Results and conclusions

The experimental values of elastic scattering cross-sections are given in table 2. In the case of tantalum and molybdenum, and in the case of lead at 50, 70 and 115°, Ge (Li) detector values were not available previously. The earlier results for lead and tantalum, obtained with 1·33 MeV gamma rays at large angles (Basavaraju and Kane 1970), are in excellent agreement with those given in table 2.

In figures 5 and 6, the present experimental results for lead are shown along with the earlier Ge(Li) detector values. Although the source strength was smaller by a factor of at least 300 than that used in the earlier experiments, there is good agreement among the various experimental values. Figures 7 and 8 show the results for tantalum. The dashed curves in figures 5 to 8 represent theoretical values of cross-sections obtained by neglecting the Delbrück amplitudes altogether. The solid curves represent the theoretical values obtained with the inclusion of the real Delbrück amplitudes. There is fairly good agreement between experimental results and the solid curves. The disagreement at large angles, mentioned in § 1, has disappeared. However, one tantalum point for 1·33 MeV gamma rays at 30·3° is significantly lower than the solid curve. The experimental values for lead between 30 and 60° tend to lie somewhat lower than the solid curves in figures 5 and 6. The origin of the small but systematic deviations upto about 60° between experiment and theory is not known.

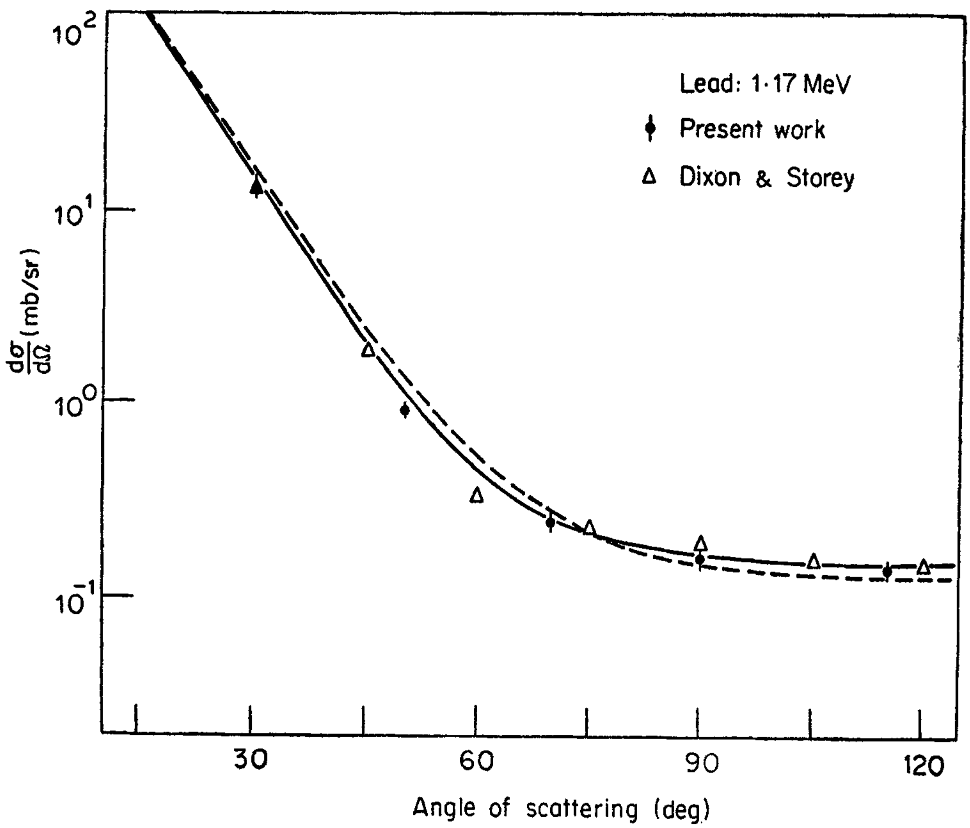

Figure 6. Elastic scattering cross-sections of lead for 1·17 MeV gamma rays.

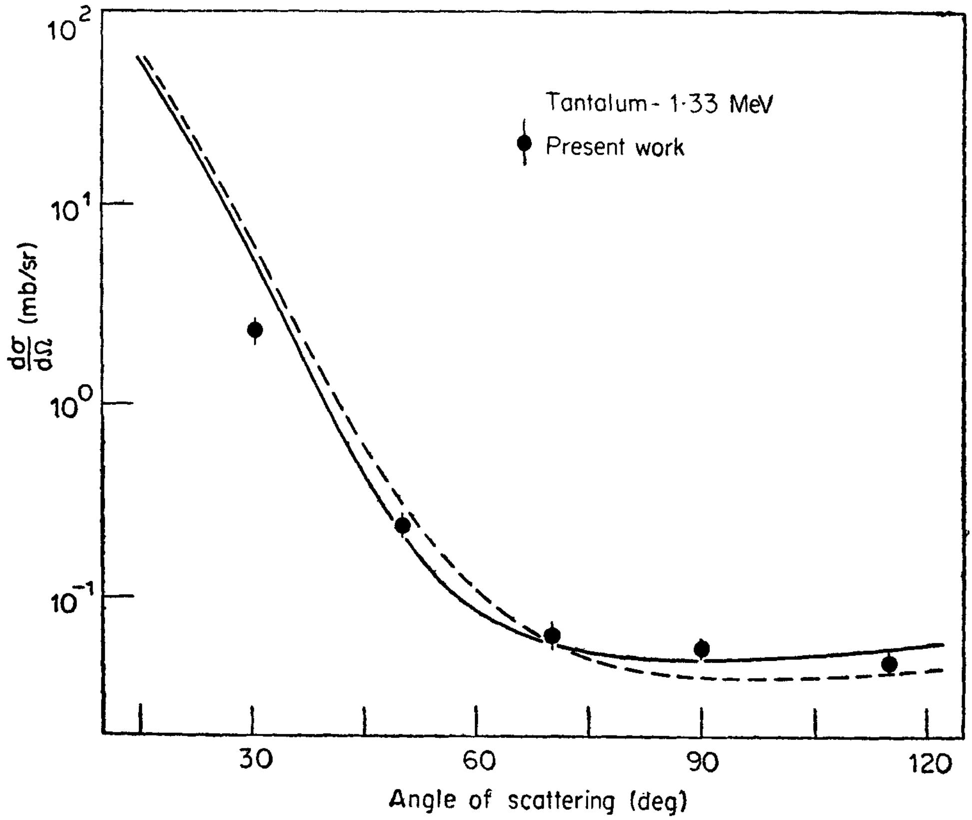

Figure 7. Elastic scattering cross-sections of tantalum for 1·33 MeV gamma rays.

In the case of molybdenum, the experimental errors are large on account of the smallness of the elastic scattering cross-sections. The theoretical Rayleigh amplitudes for molybdenum have to be obtained at present by the procedure outlined in § 4. The reliability of this procedure over a large variation in atomic number Z from 82 to 42 is not yet established. Further, the calculated Delbrück amplitudes are proportional to the square of Z and are therefore relatively small for molybdenum. As a result of this combination of circumstances, the data do not permit a preference between calculations with and without the Delbrück amplitudes. Hence, these data are not shown graphically. In spite of the above mentioned situation for molybdenum, there is now substantial evidence for the real Delbrück amplitudes at energies of about one MeV. Of course, the above conclusion relies on the assumed smallness of Coulomb corrections to the Delbrück amplitudes. Importance of a proper evaluation of these corrections has been emphasized recently (Maximon 1977).

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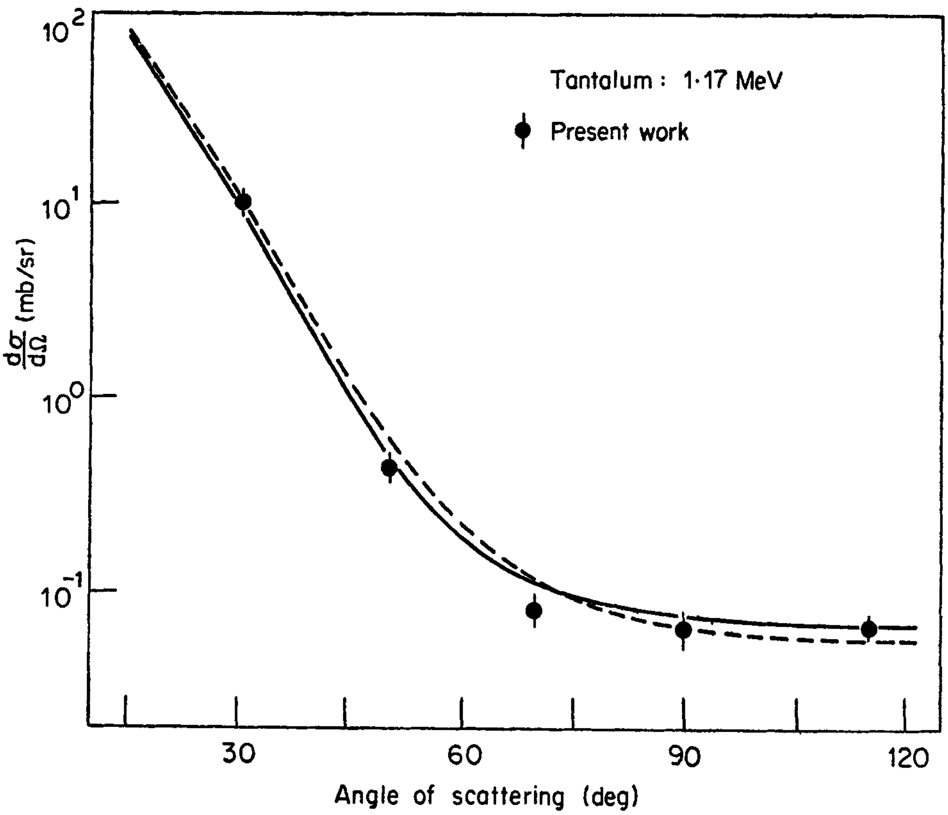

Figure 8. Elastic scattering cross-sections of tantalum for 1·17 MeV gamma rays.

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